Advanced Colliders
Physics Motivation

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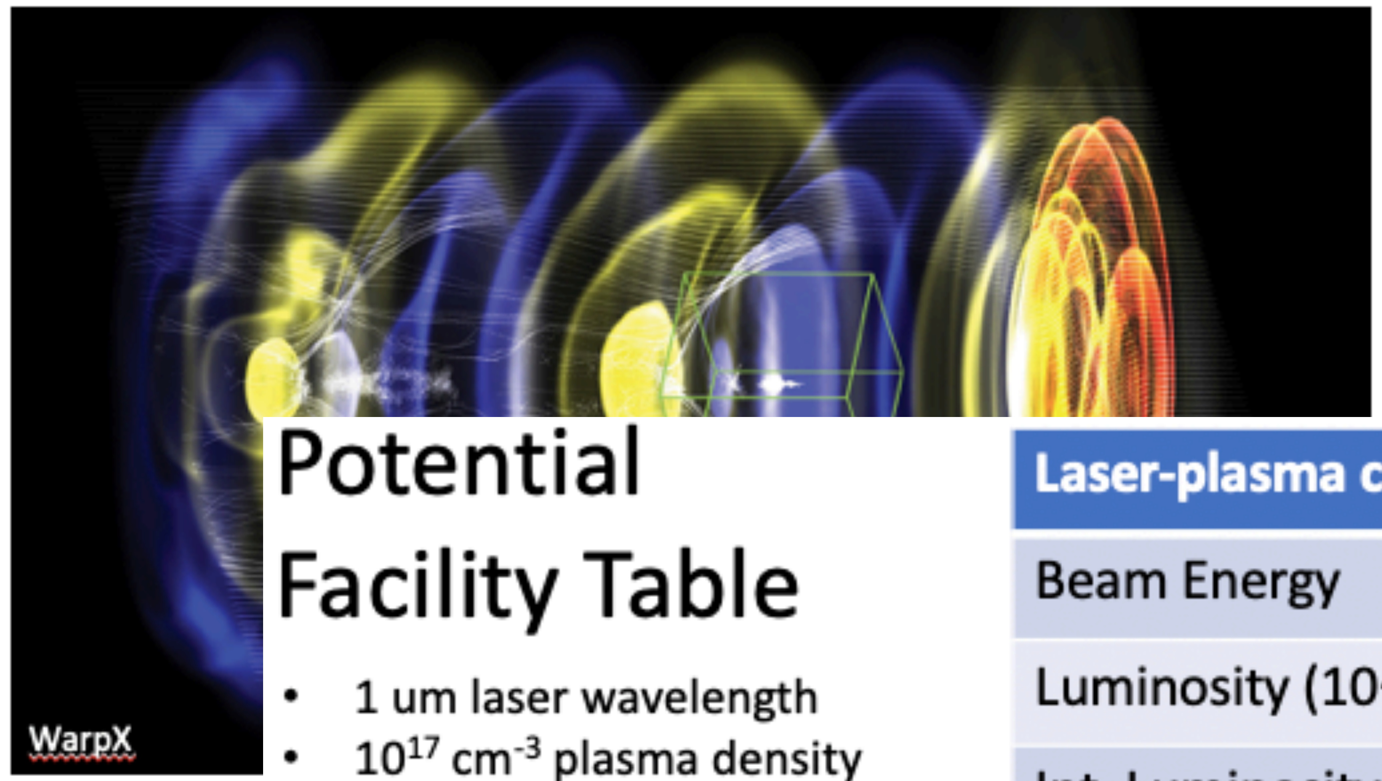
Really a Different Agora -AF6

Plasma – Laser Wakefield Accelerators
1 TeV and beyond

Carl Schroeder
BELLA Center
Lawrence Berkeley National Laboratory

July 2020 Joint EF/AF meeting



Potential Facility Table

- 1 um laser wavelength
- 10^{17} cm^{-3} plasma density

Schroeder et al. NIMA (2016)

- ALL PARAMETERS NEED SYSTEM-INTEGRATED DESIGN STUDY

Laser rep. rate not available with present laser technology

- Upgrade potential: Same laser system for 1, 3, 30 TeV

Laser-plasma collider - e-/e+		1 TeV cme	3 TeV cme	30 TeV cme
Beam Energy	TeV	0.5	1.5	15
Luminosity (10^34)	cm-2 s-1	1	10	1000
Int. Luminosity	ab-1/yr	0.18 (5000hrs)	1.8 (5000hrs)	18 (5000hrs)
Beam dE/E at IP				(Y>>1 regime)
Transv. Beam sizes at IP x/y	nm	50 / 1	10 / 0.5	0.2 / 0.2
Rms bunch length / beta*	mm	0.0085 / 0.1	0.0085 / 0.1	0.0085 / 0.2
Crossing angle	urad	TBD: similar to conventional collider designs		
Rep. frequency	kHz	47	47	47
Bunch spacing	us	21	21	21
# of IPs		1	1	1
# of bunches		1	1	1
Length (2x main linac tunnel)	km	0.44	1.3	13
Facility site power (2 linacs)	MW	105	315	3151
Cost range	$B US	requires laser tech maturity before estimate		
Timescale till operations		>30 years	>30+ years	>30++ years

Maybe a niche reference...

Different Agora

What's the physics case?

Alternative path to 10 TeV?

Path beyond!

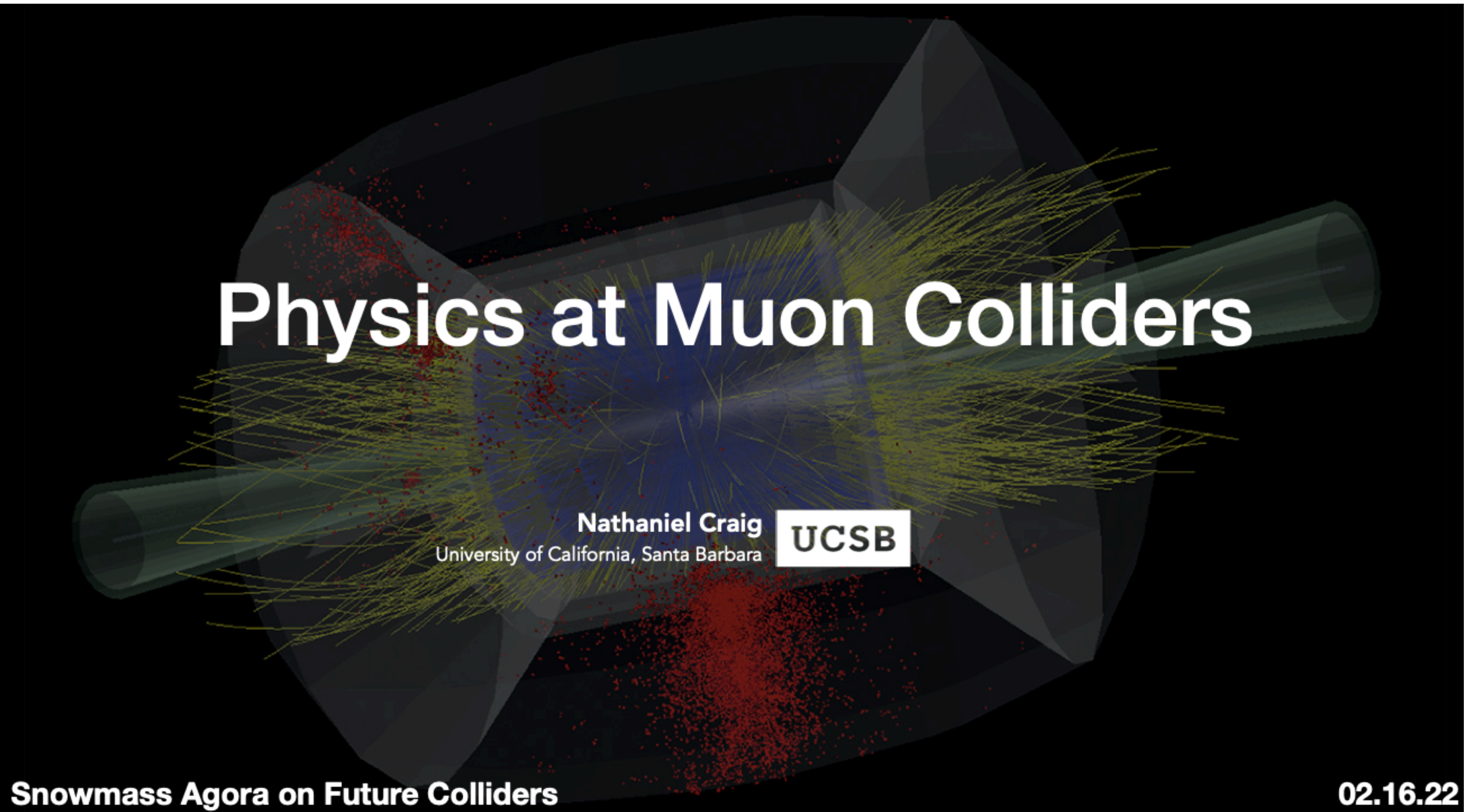
Different Agora

What's the physics case?

?

Alternative path to 10 TeV?
(Compared to pp and muon collider)

Path beyond!



Provided e^+e^-
Not e^-e^- or $\gamma\gamma$

Outside my purview on readiness see next talks and discussion

Different Agora

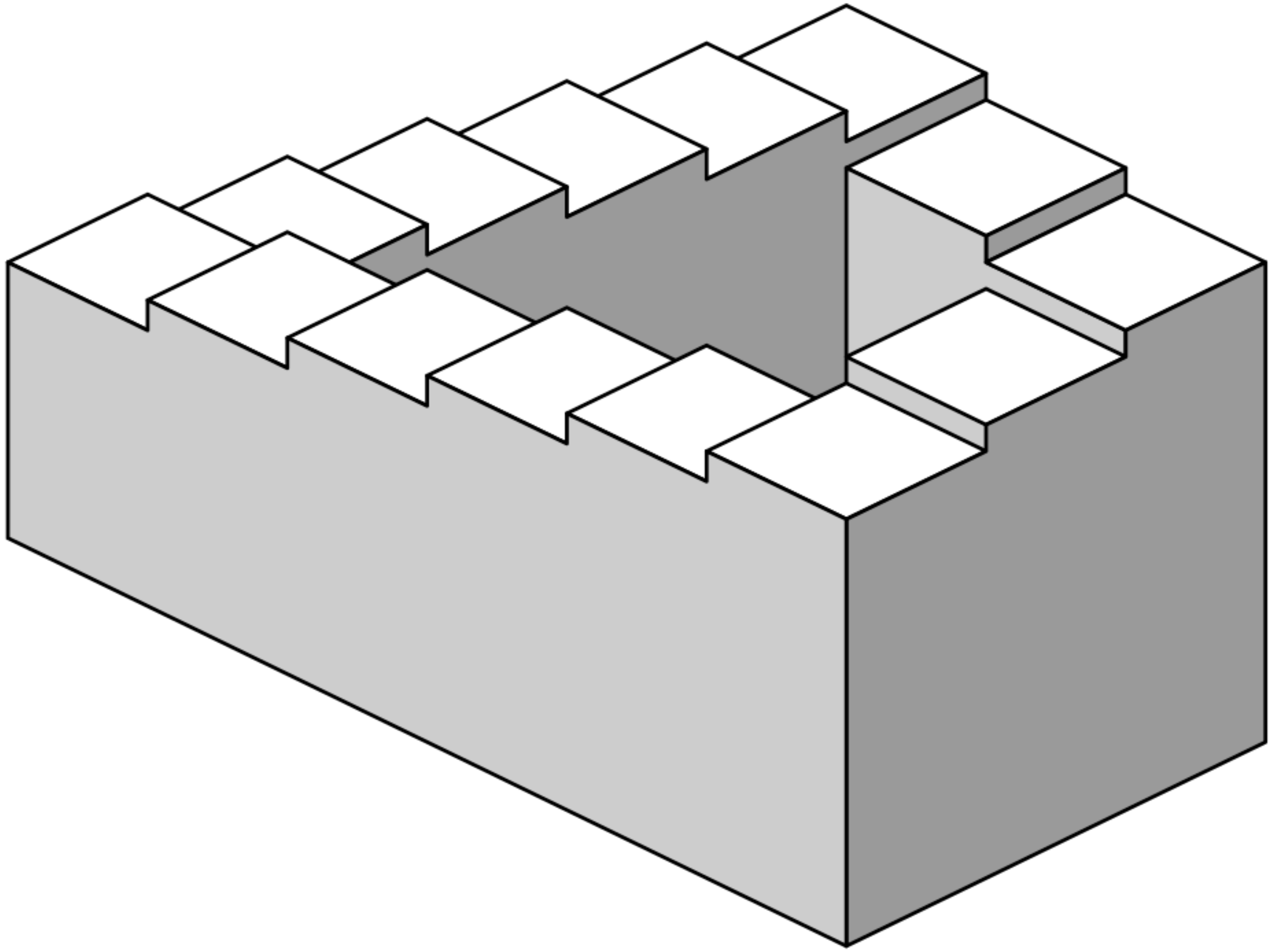
What’s the physics case?

?

Alternative path to 10 TeV?

Path beyond!

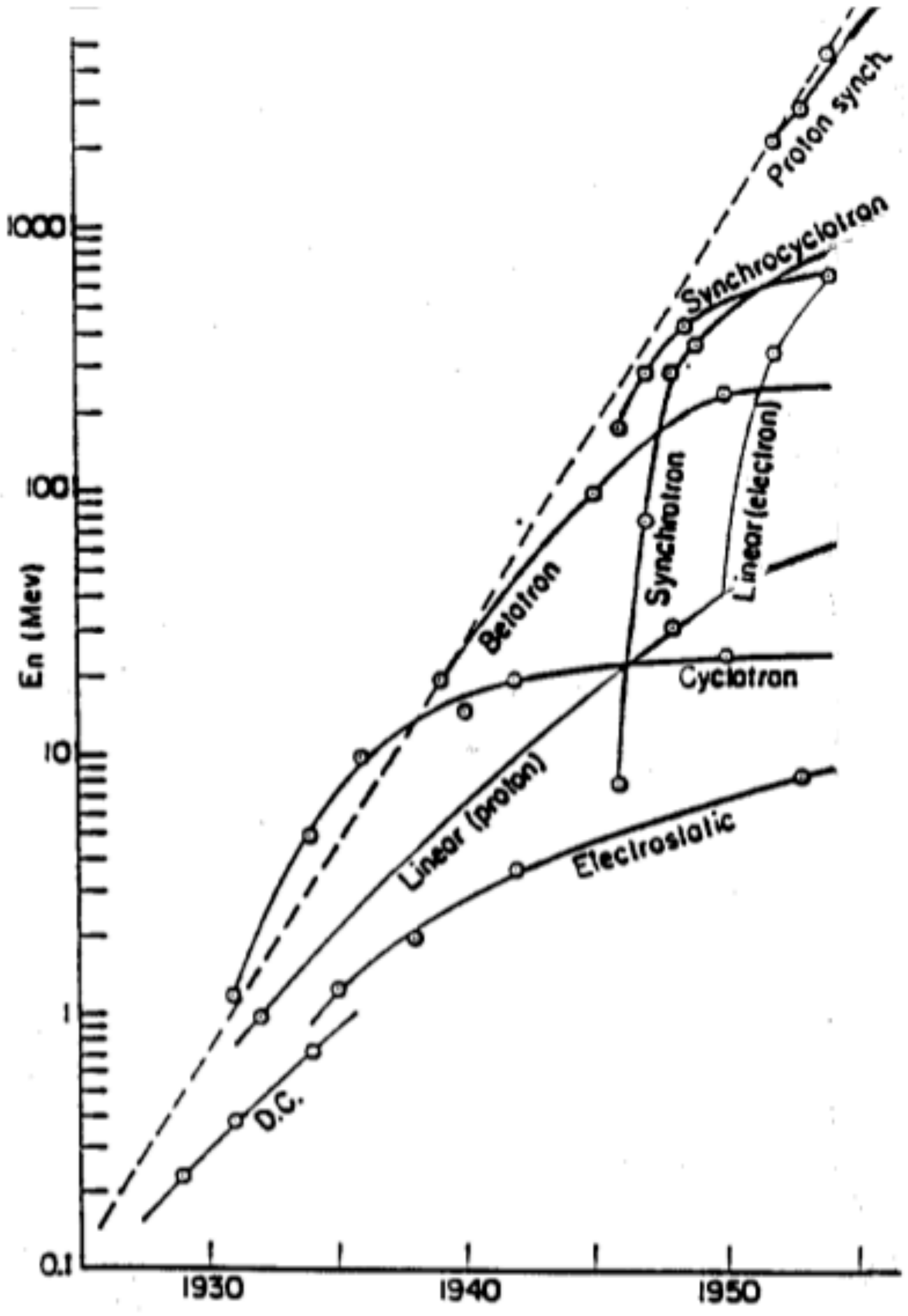
Theorists always want more energy and luminosity



Is there an end in sight?

When does that path end?

Accelerators used to have their version of a Moore's law



Start this innovation again now and we only need…about 300 years

Livingston's Law - Doubling of energy every six years

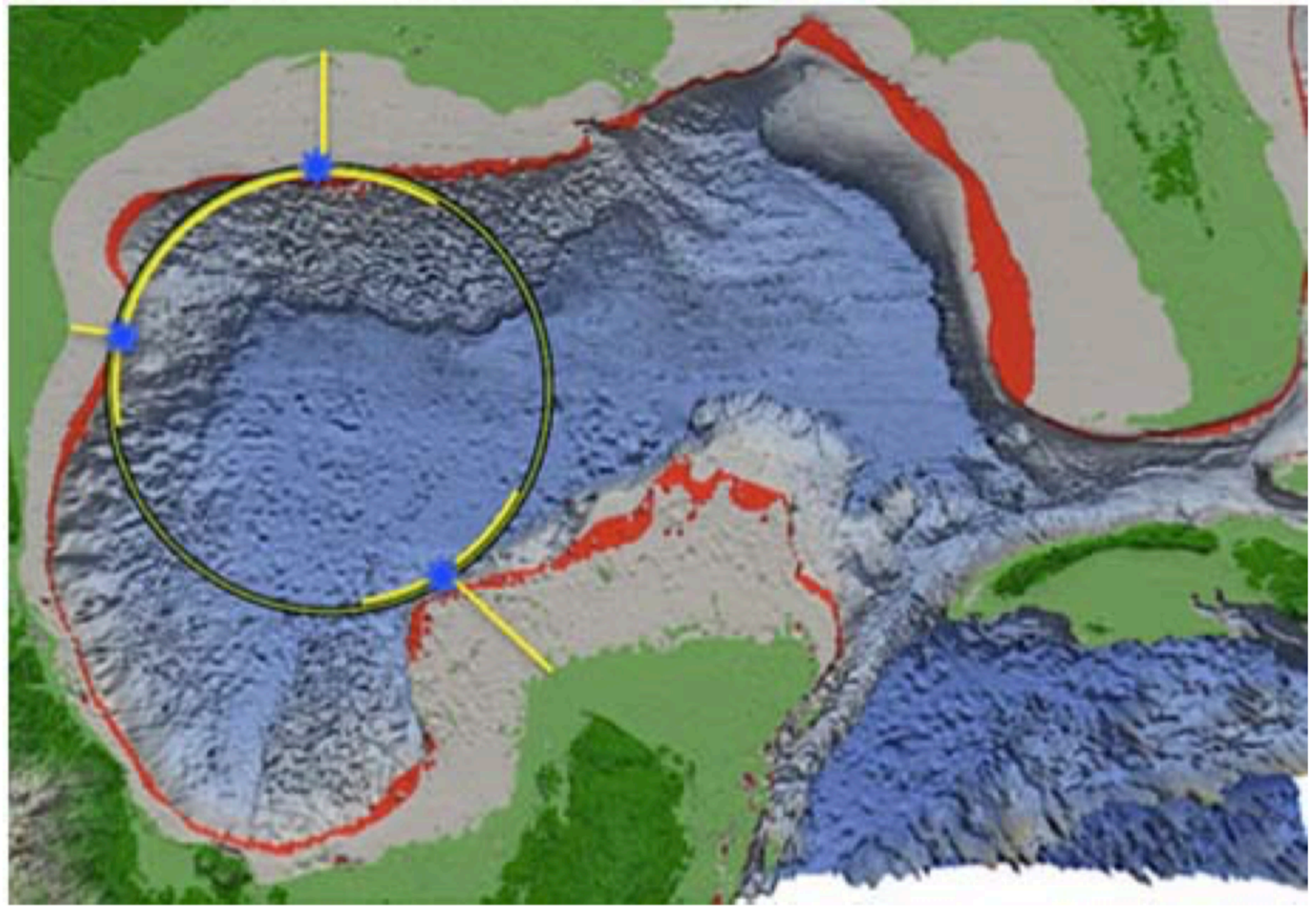
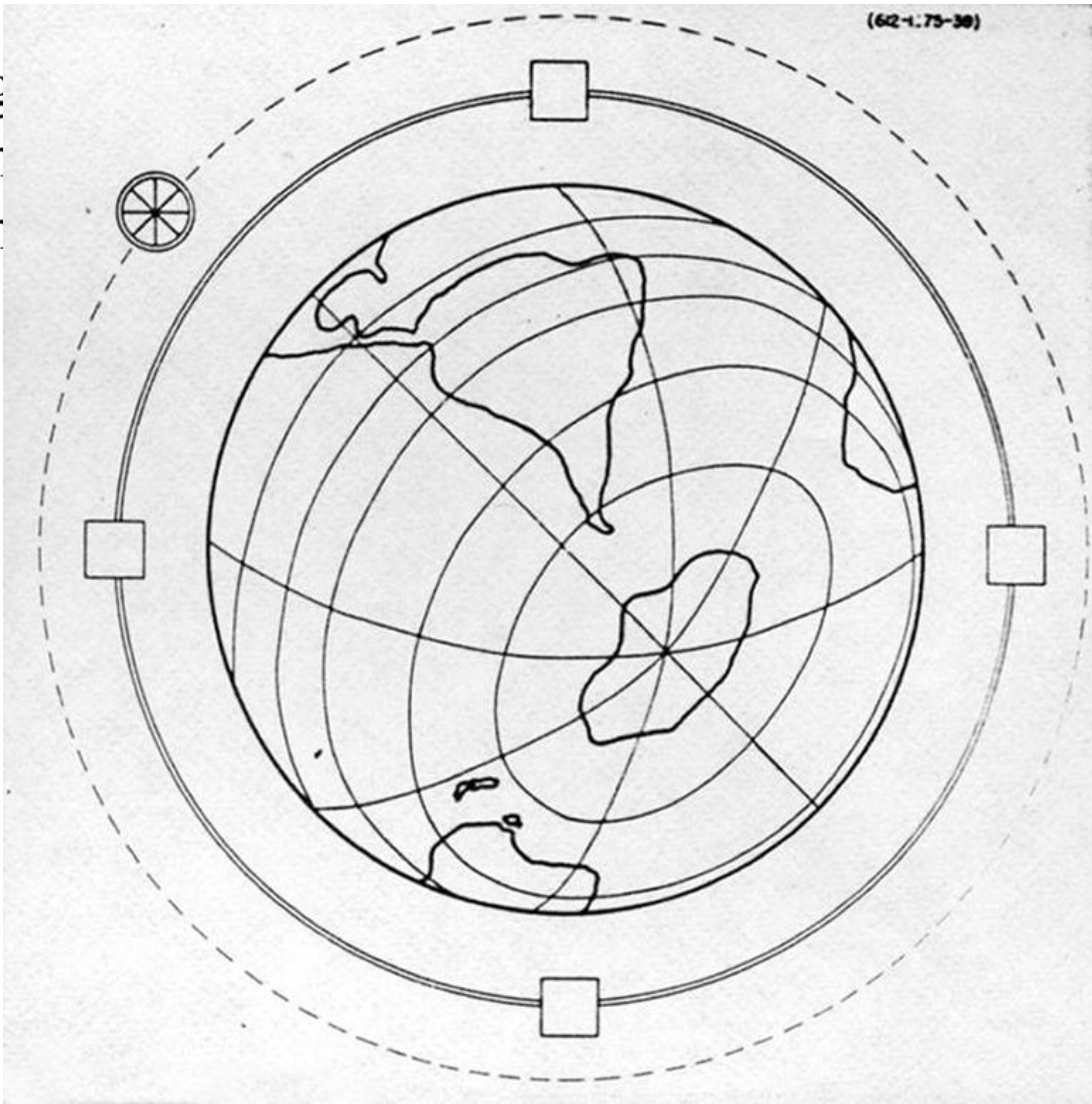
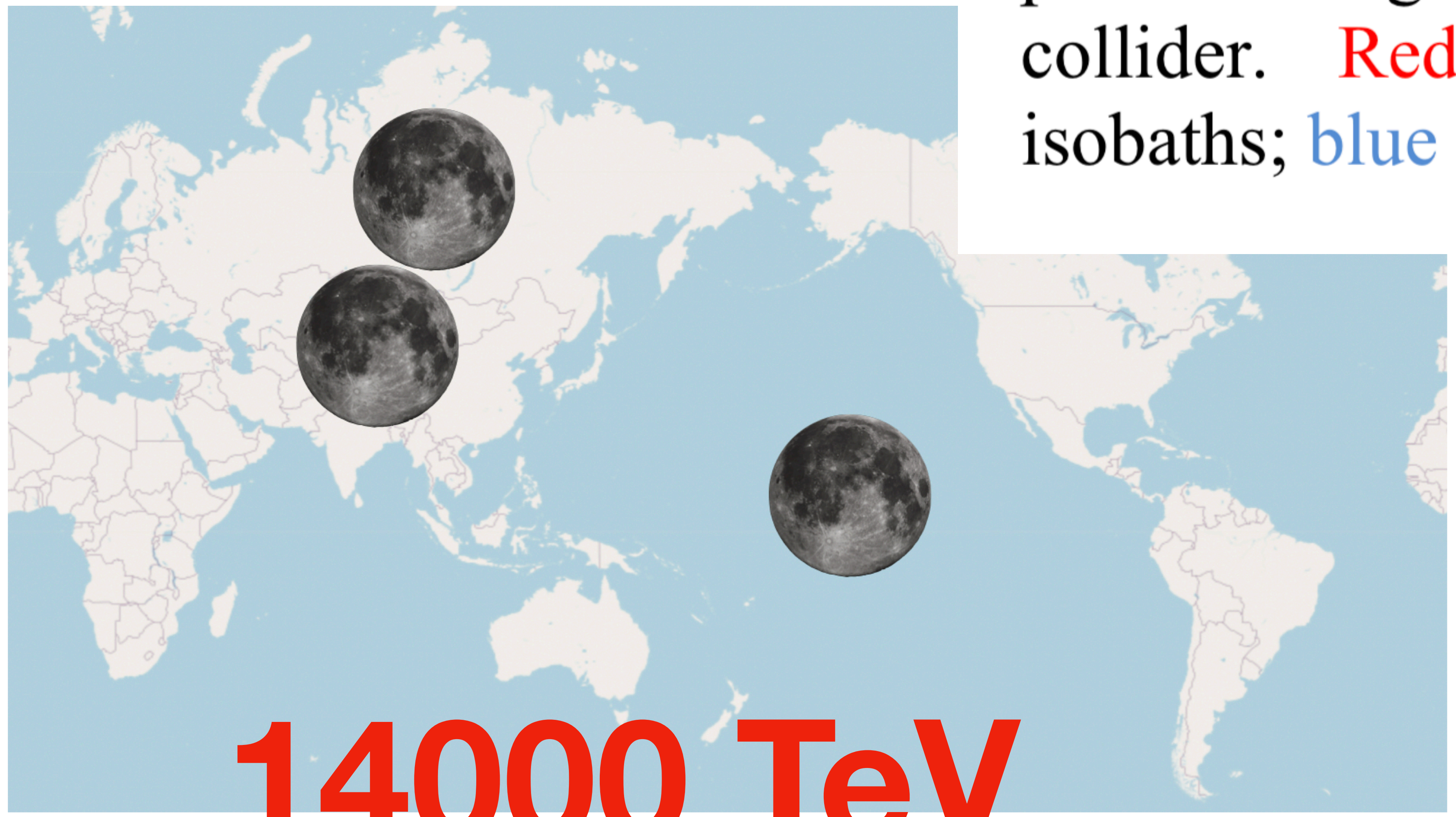


Figure 2: Bathymetry of the Gulf of Mexico, showing potential alignment of a 1,900 km circumference hadron collider. Red =100➔200 m isobaths; gray = 0-100 m isobaths; blue = detectors; green = surface topography.

500 TeV

5000 TeV





14000 TeV

FIG. 1. Three potential Earth-based sites for a circular collider approximately the same size as a collider encircling the Moon of ~11000 km in circumference, represented by images of the Moon overlaid on a map of the surface of the Earth. Each potential Earth-based site for such a large collider project is accompanied by significant geographical, technological, or political challenges. Adapted from Ref. [13] and Ref. [14].

Alas...

We're *still* trying to implement these

PHYSICS WITH LINEAR COLLIDERS IN THE TEV CM ENERGY REGION

F. Bulos[†], V. Cook[*], I. Hinchliffe[**], K. Lane[††],
D. Pellet[⊗], M. Perl[†], A. Seiden[Δ], H. Wiedemann[†]

Design Goals

The physics as described in previous sections calls for maximum center-of-mass energies of at least 1000 GeV and possibly above. We will therefore explore the parameters of linear colliders from about 400 GeV up to 2000 GeV. As we mentioned before, the luminosity is limited by the electrical power available to the collider. In this study we have arbitrarily assumed a maximum electrical power of

$$P_{AC} = 100\ \text{MW} \qquad \text{(VII.1)}$$

Snowmass 1982

HADRON HADRON COLLIDER GROUP*

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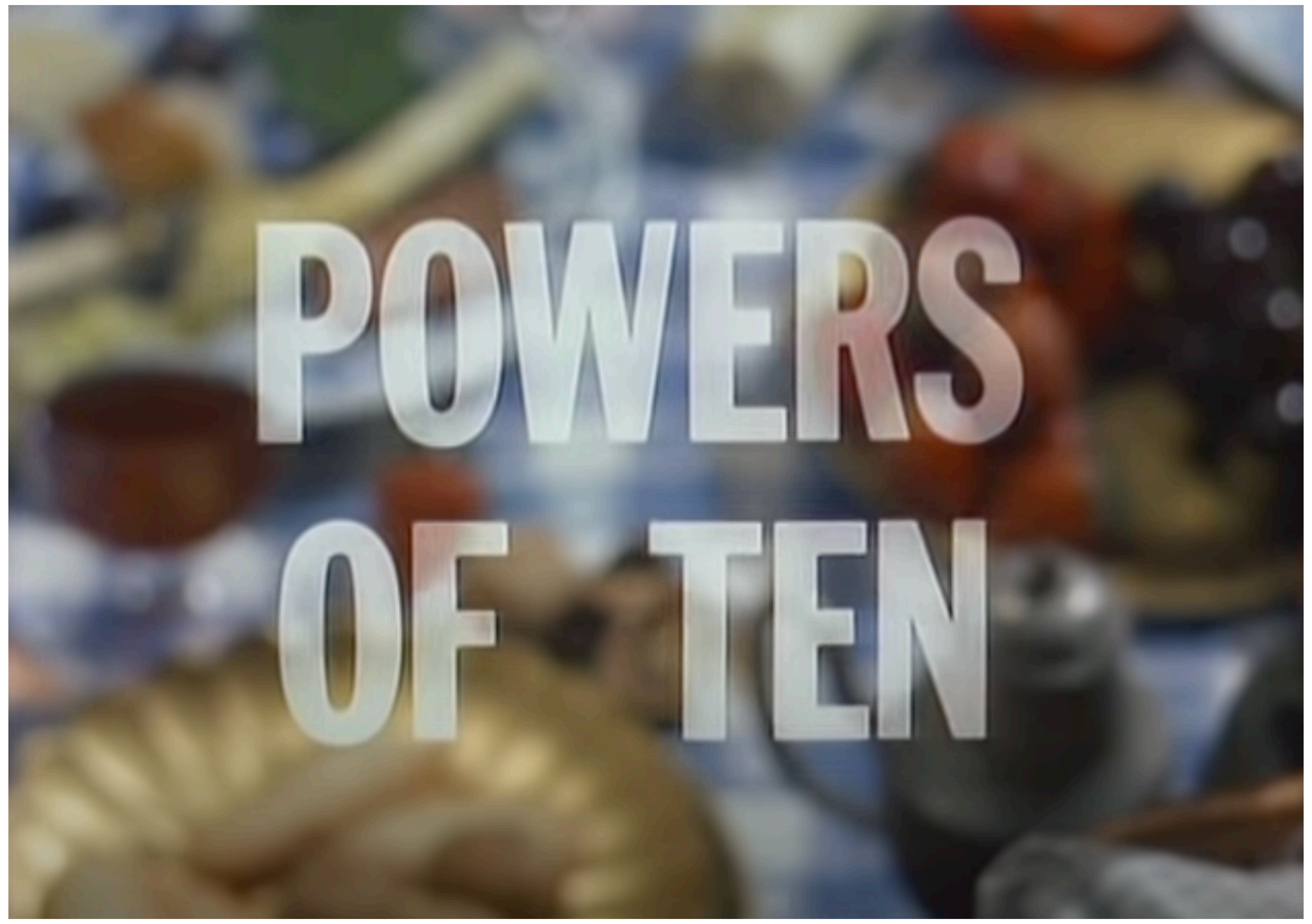
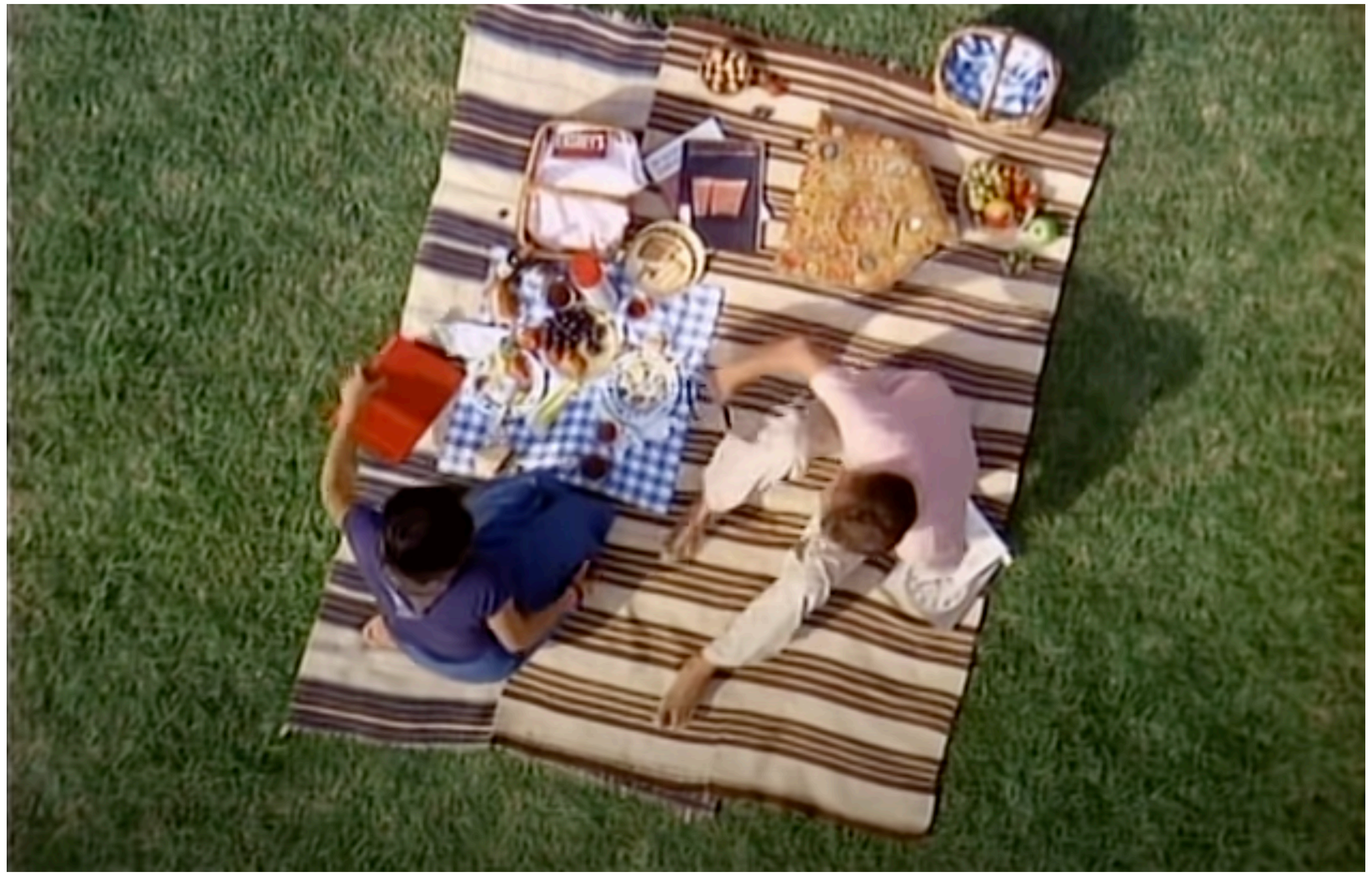
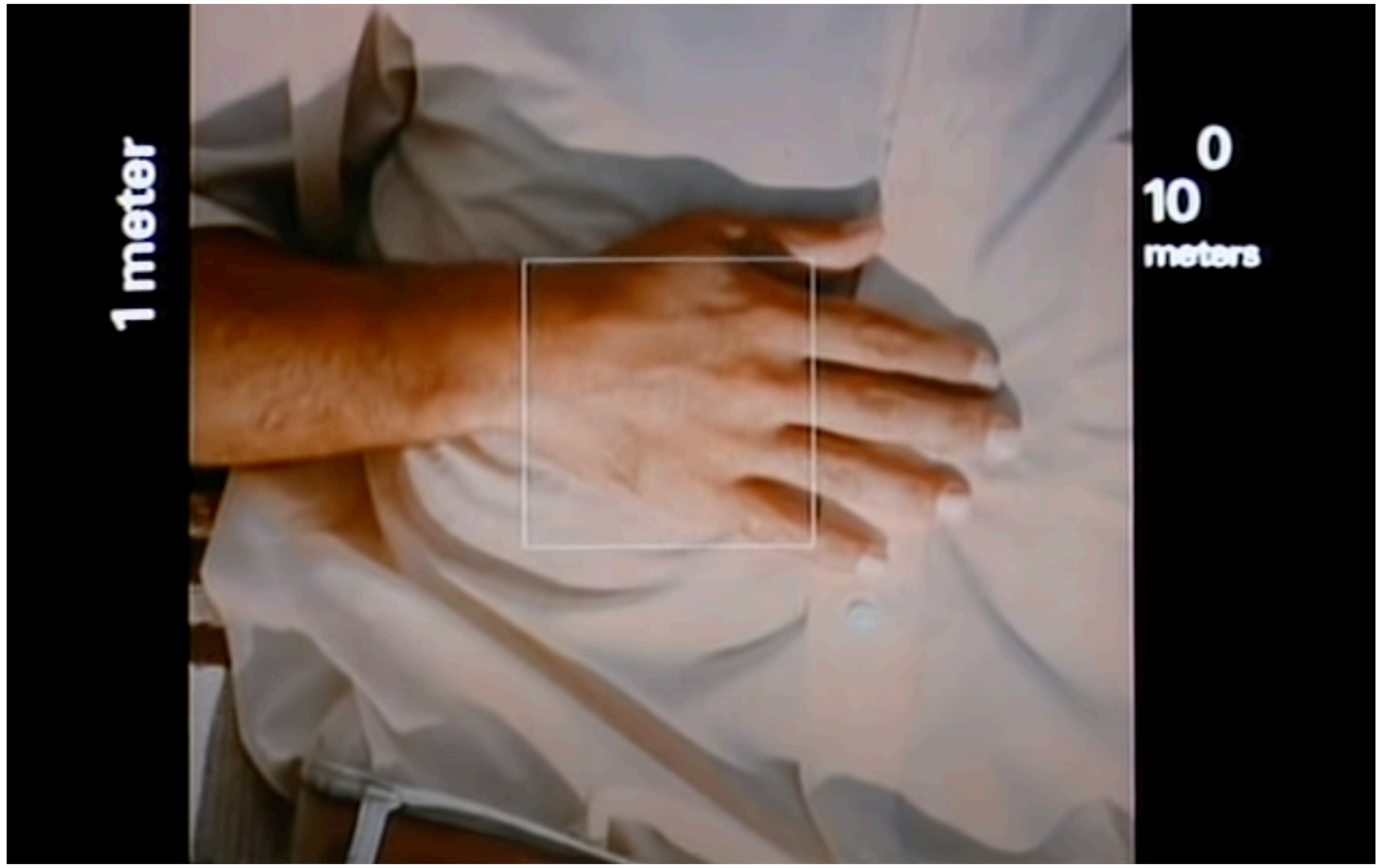
I. Introduction

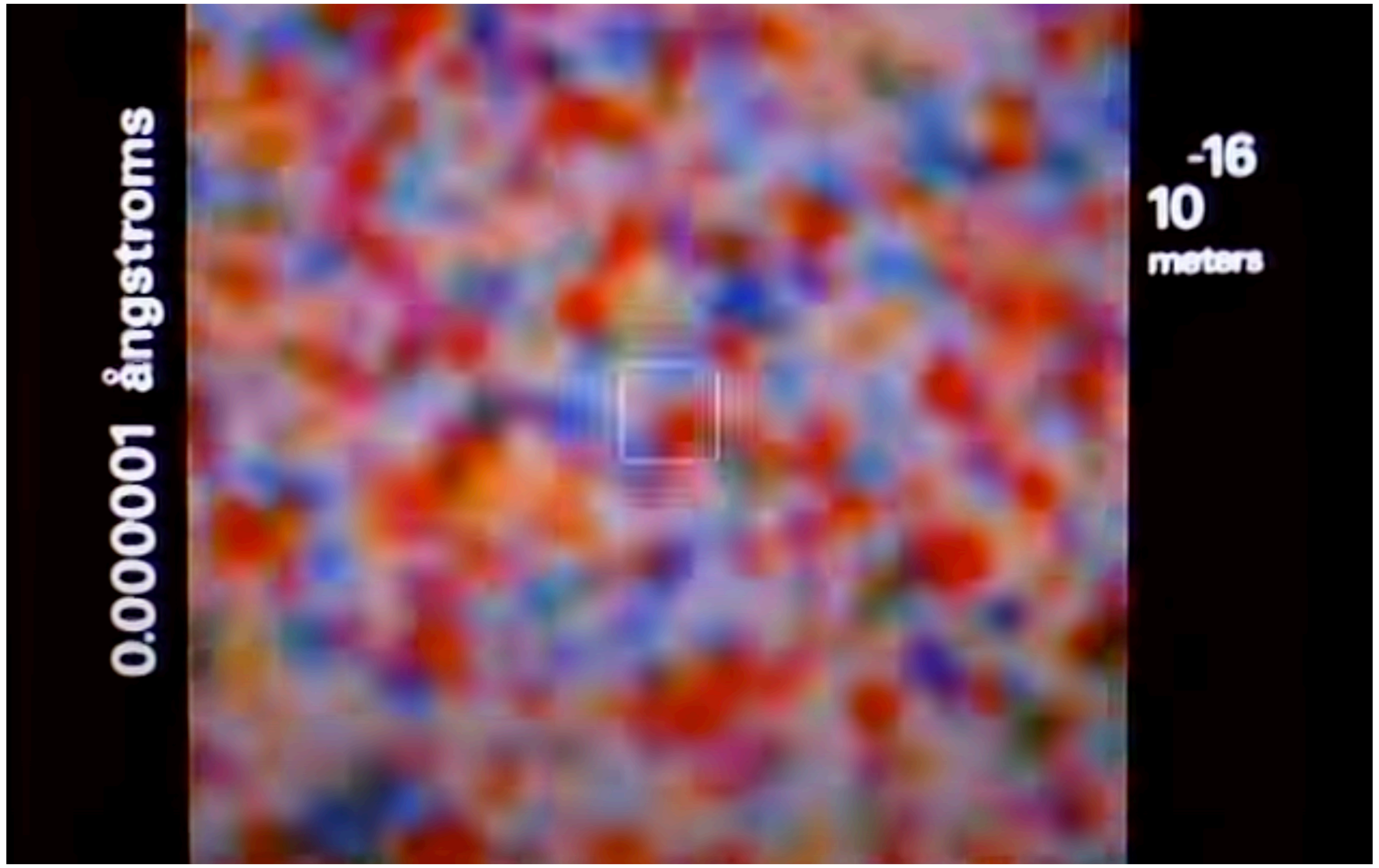
The objective of this group was to make a rough assessment of the characteristics of a hadron-hadron collider which could make it possible to study the 1 TeV mass scale. Since there is very little theoretical guidance for the type of experimental measurements which could illuminate this mass scale, we chose to extend the types of experiments which have been done at the ISR, and which are in progress at the SPS collider to these higher energies. Initially we chose to call these experiments "bellwether experiments" for reasons of convenience. In the absence of any alternative predictions we assumed that the cross sections for these standard experiments could be obtained either by extrapolating perturbative QCD models of hadrons to center of mass energies of 40 TeV or by extrapolating phenomenological parameterization of data obtained from experiments done in the center of mass energy range of 20 to 60 GeV to 40 TeV. For each bellwether we asked up to what mass (or momentum transfer Q) could a significant (> 100) number of events be seen in 10^7 seconds. While it is unlikely

Snowmass 1982


POWERS
OF TEN




1 meter
10^{0}
meters


0.000001 ångstroms
10^{-16}
meters

A vision for the future

1 TeV	10 TeV	100 TeV
LHC	FCC-hh	AC
ILC	SPPC	
CLIC	MuCol	
	AC?	

Why motivate the 100 TeV partonic scale isn't 10 TeV enough?

Motivated Targets

Energy gives precision

Many ideas from an LOI
previous talk by Raman Sundrum
July 2020

Precision/Complementarity

- More precision (without deviation) means we must prepare for higher energies!
  - Simple fact about decoupling and Quantum Field Theory
  - W mass example - lots of ideas naturally live in the multi-TeV range
  - g-2, flavor anomalies
- Lot of other probes of high energy physics not at high energy…
  - CP violation
  - Flavor
  - Gravitational Waves

Complementarity with other Frontiers

Indirect hints are hard - we want to be able to test them "directly" whether it's from EF or somewhere else, and there are a lot or improvements coming in the future

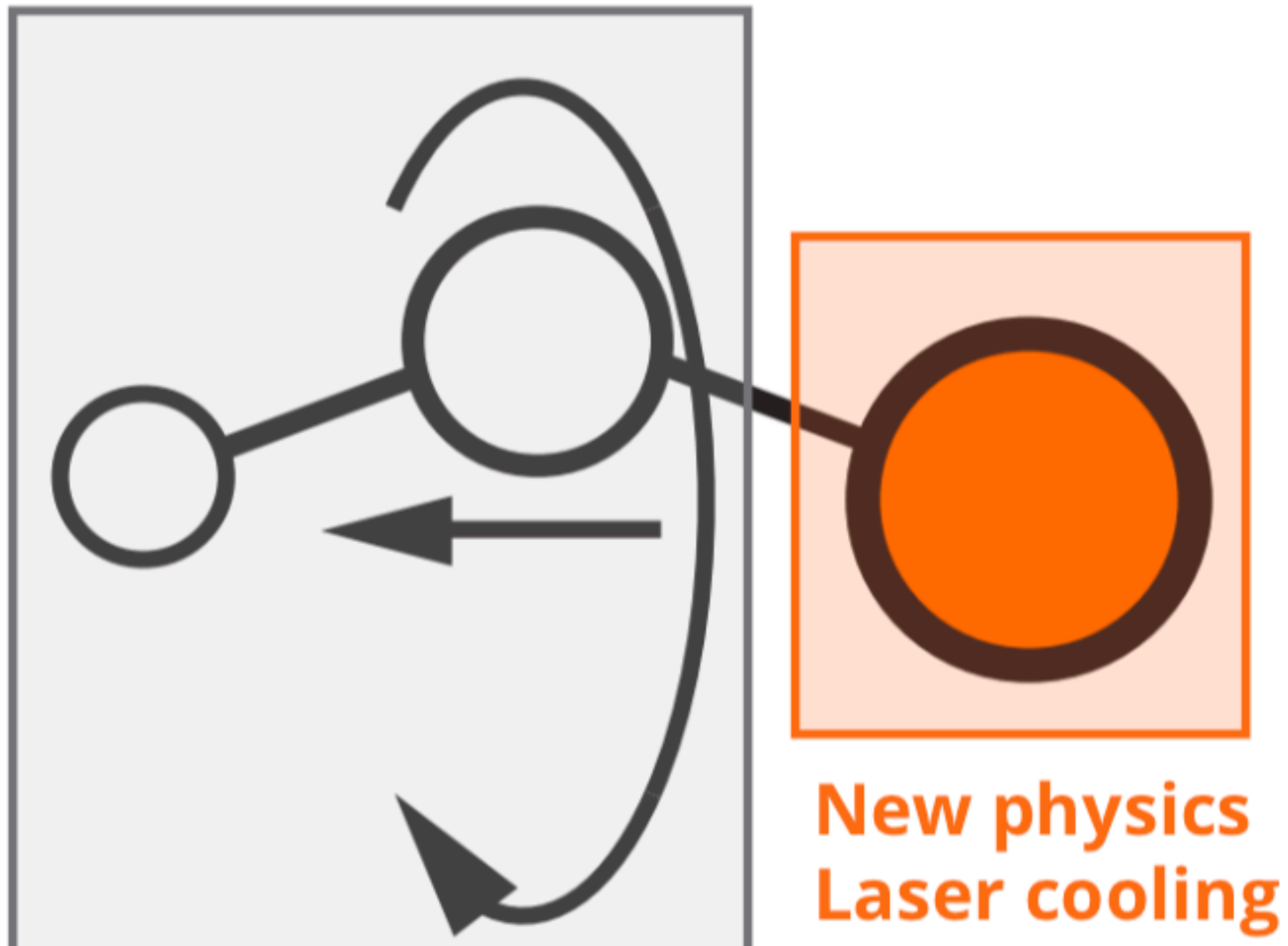
Gravitational Waves, Astrophysics, Dark Matter, Rare Processes

Complementarity: Electric Dipole Moments (EDMs)

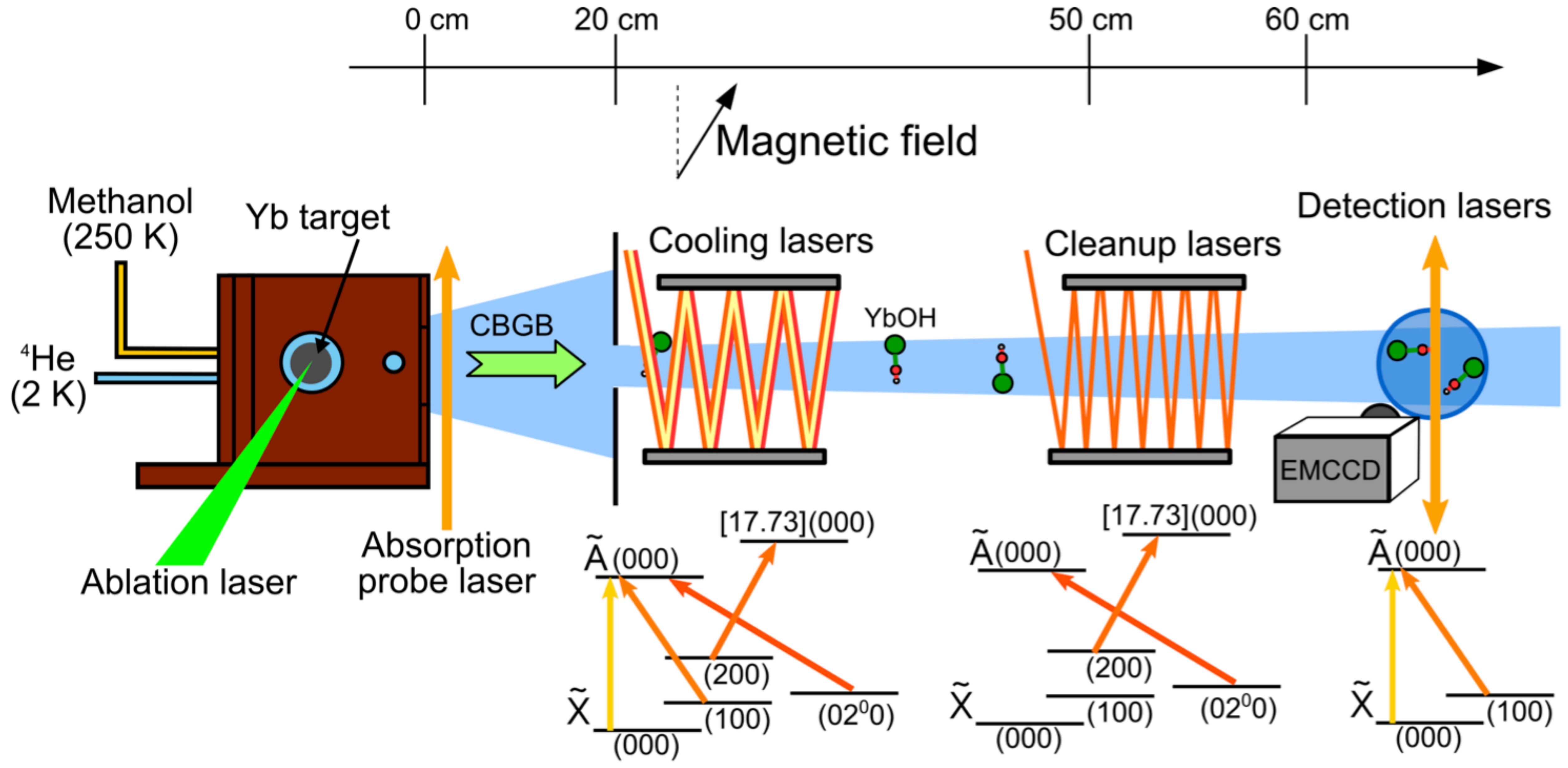
Precision on the Horizon

One of several parallel approaches:

Polyatomic Molecules (e.g., YbOH)
Hutzler, Kozyryev 1705.11020



from slide by N. Hutzler

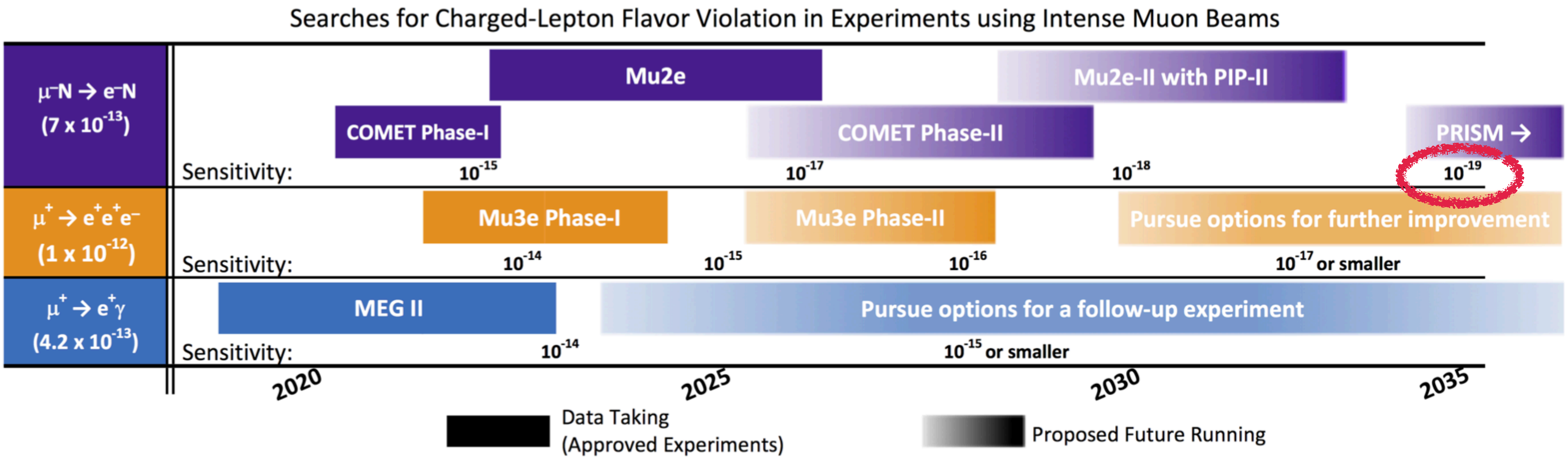


Laser cooling achieved (Augenbraun et al., 1910.11318)

Electron EDM: $10^{-29} e\,\mathrm{cm} \longrightarrow 10^{-32} e\,\mathrm{cm}$ **!**

Complementarity: Charged Lepton Flavor Violation (CLFV)

Precision on the Horizon



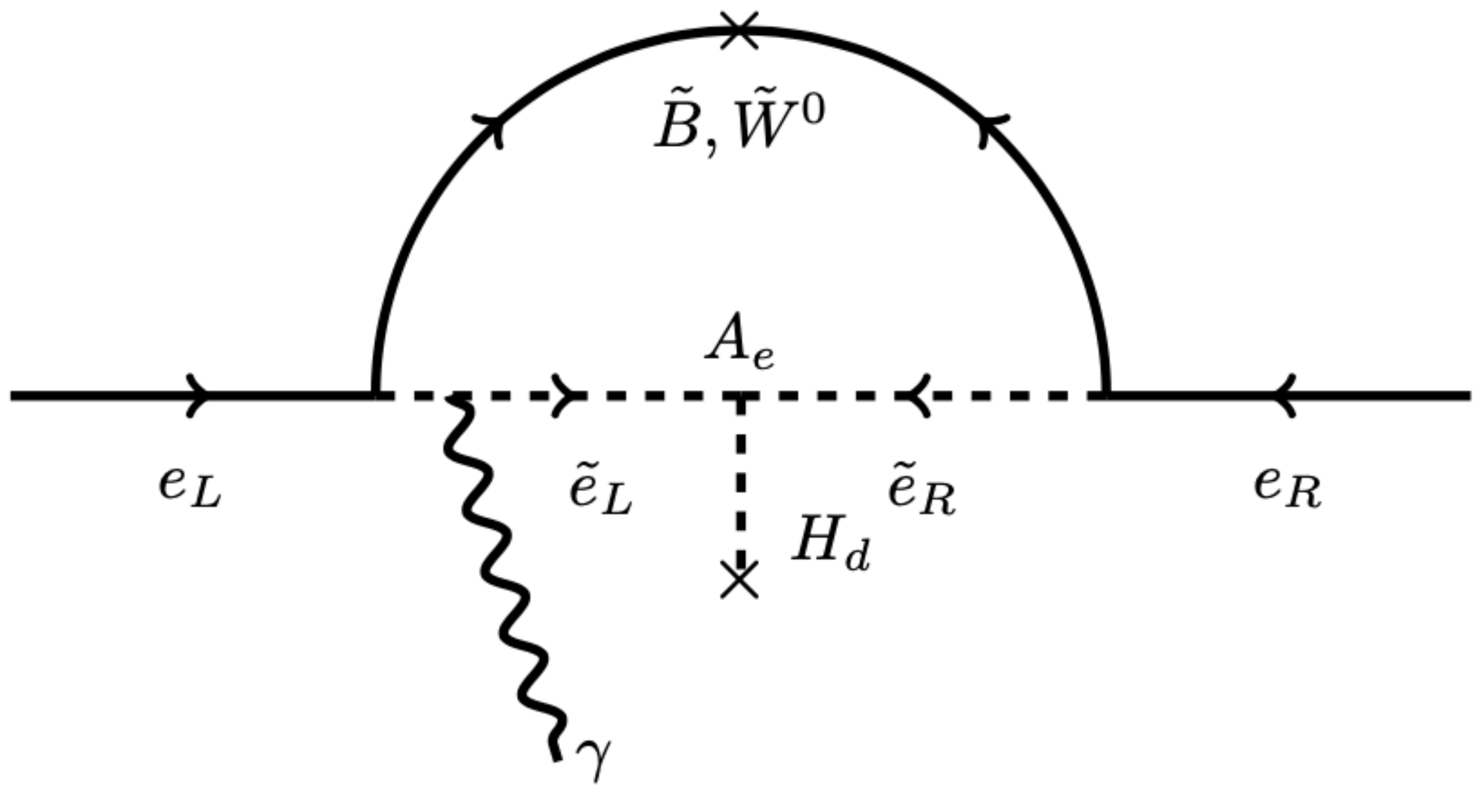
Source: Baldini et al., 1812.06540, submission to 2020 European Strategy from COMET, MEG, Mu2e and Mu3e collaborations

Complementarity: Physics Reach

The Bottom Line: Probe 10s of TeV to PeV Energy Scales!

EDM, 1-loop

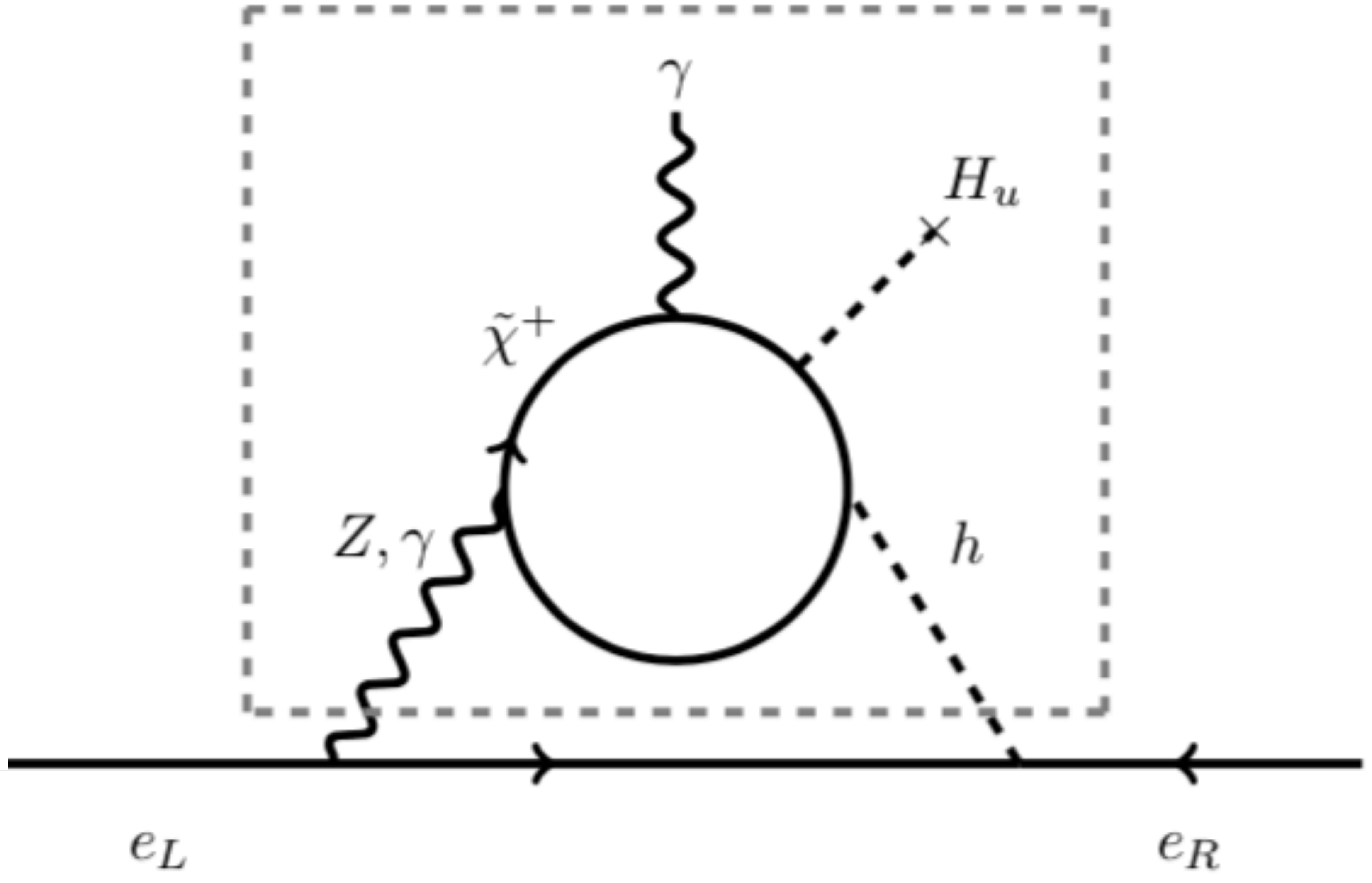
electron-flavored



10^{-32} e cm $\Longrightarrow$ ~ **1 PeV (!)**

EDM, 2-loop Barr-Zee

Anything Higgs+EWK



10^{-32} e cm $\Longrightarrow$ ~ **50 TeV (!)**

$\mu \rightarrow e$, 1-loop, flavor violating

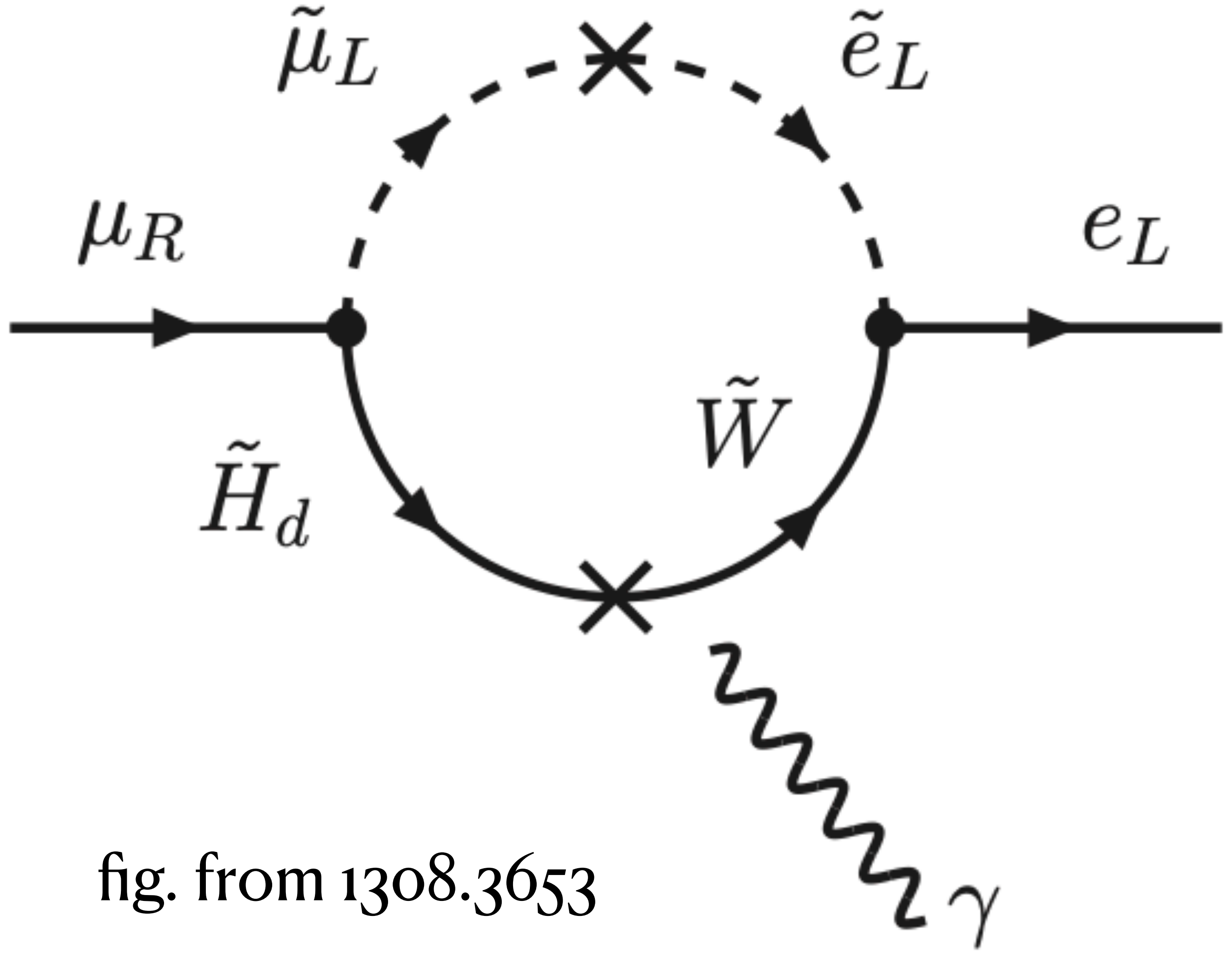


fig. from 1308.3653

Altmannshofer, Harnik, Zupan

10^{-19} on Al $\Longrightarrow$ ~ **50+ TeV (!)**

(w/ electron Yukawa spurions on all diagrams)

Gravitational Waves From Phase Transitions

Gravitational waves are the only direct observational probe before CMB in Cosmology

Search for the isotropic stochastic background using data from Advanced LIGO's second observing run

The LIGO Scientific Collaboration and The Virgo Collaboration
(Dated: September 9, 2019)

The stochastic gravitational-wave background is a superposition of sources that are either too weak or too numerous to detect individually. In this study we present the results from a cross-correlation analysis on data from Advanced LIGO's second observing run (O2), which we combine with the results of the first observing run (O1). We do not find evidence for a stochastic background, so we place upper limits on the normalized energy density in gravitational waves at the 95% credible level of $\Omega_{GW} < 6.0 \times 10^{-8}$ for a frequency-independent (flat) background and $\Omega_{GW} < 4.8 \times 10^{-8}$ at 25 Hz for a background of compact binary coalescences. The upper limit improves over the O1

Stochastic Gravitational Wave Signal is Very Hard (and astrophysics constributions!)-

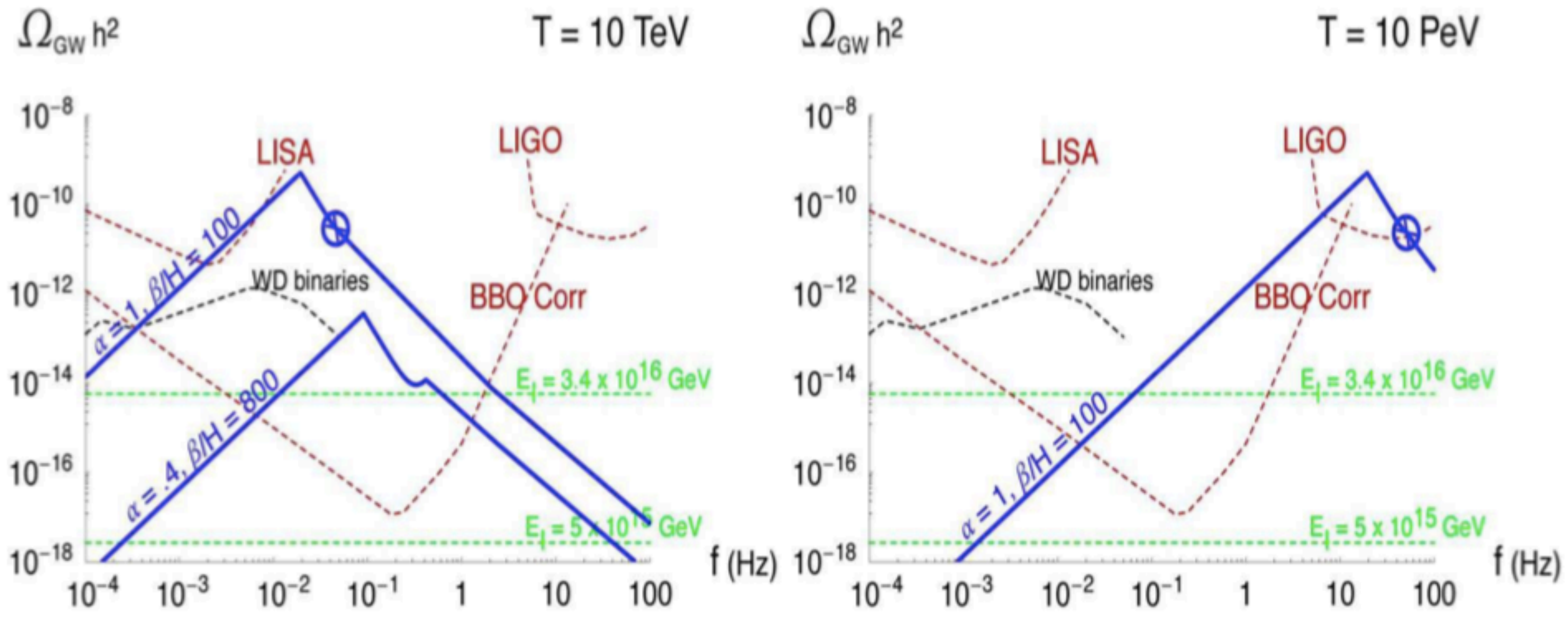
Would it be trusted as signal for BSM without complementary measurements?

Gravitational Waves From Phase Transitions

Stochastic Gravitational Wave Signal is Very Hard - Would it be trusted as signal for BSM?

LIGO frequency band $$f \sim \mathcal{O}(10^2)\text{Hz}$$

LISA frequency band $$f \sim \mathcal{O}(10^{-3})\text{Hz}$$



Therefore if something is *observed* with future LIGO runs it points to high (PeV) scales!

LISA 2030s timescale fills in to lower, but still favors higher scales

What *assumptions* can we make about testability assuming thermal equilibrium etc

specialization to EW phase transitions tightens this up considerably

Understanding our theories better and using LHC data

Naturalness

Conventional Naturalness or “Neutral Naturalness”

Hidden sector resolutions of the little hierarchy problem

Conventional Naturalness

SM-charged partner particles → m_*

$\sqrt{1\text{ loop}}$

m_h

Natural scale of new SM-charged particles raised by ~ 4π

Neutral Naturalness (Twin Higgs, …)

m_* ← SM-charged partner particles

$\sqrt{1\text{ loop}}$

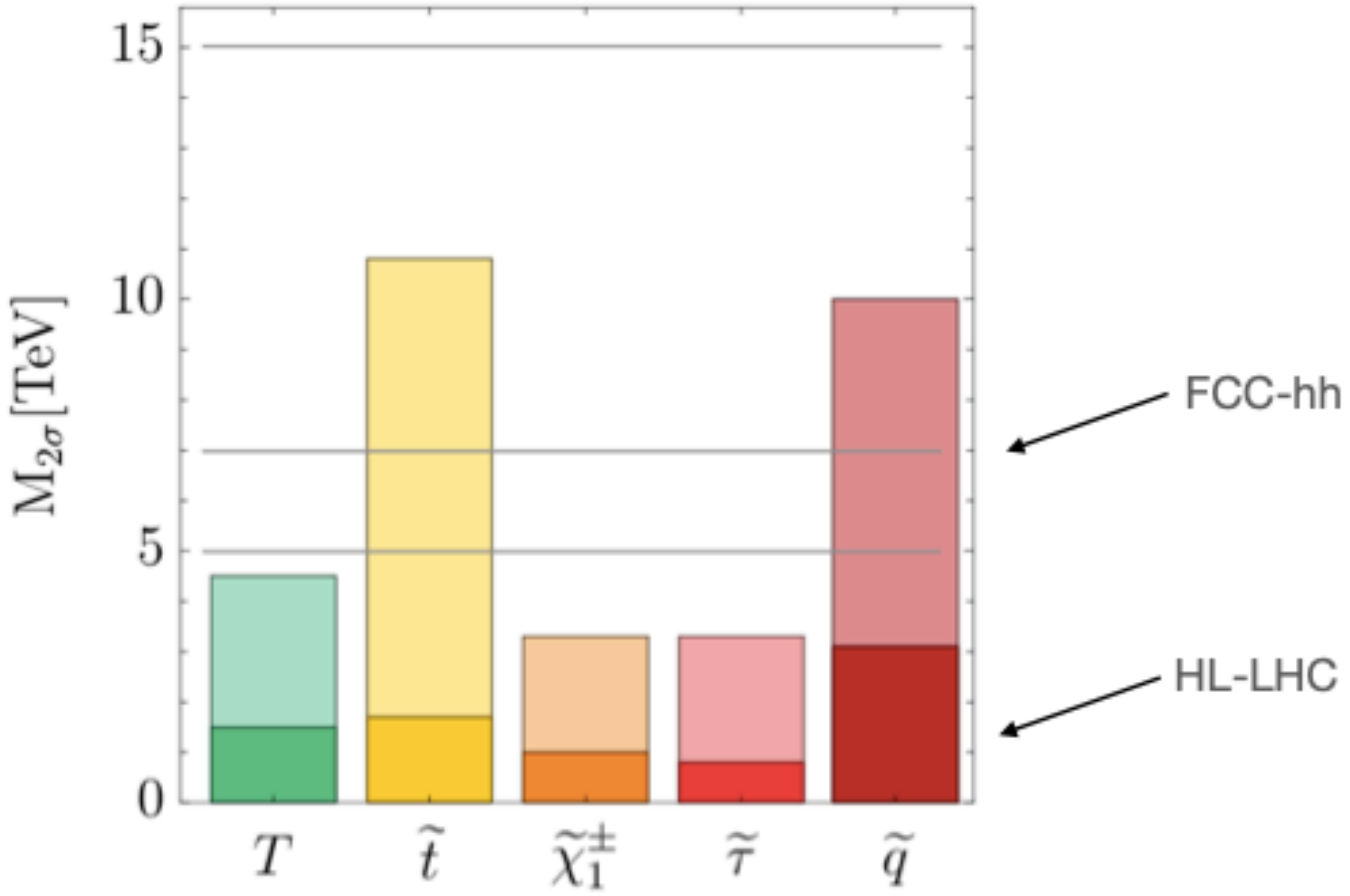
$m_{h'}$ ← SM-neutral partner particles

$\sqrt{1\text{ loop}}$

m_h

Naturalness intertwined with Higgs Mass predictions

Discovery of 125 GeV Higgs immediately implied stops could be ~ 10 TeV scale



20+ TeV lepton collider

Similar lessons from composite Higgs ideas as to the scale

Naturalness in the dark

40+ TeV lepton collider

What is required for discovery?

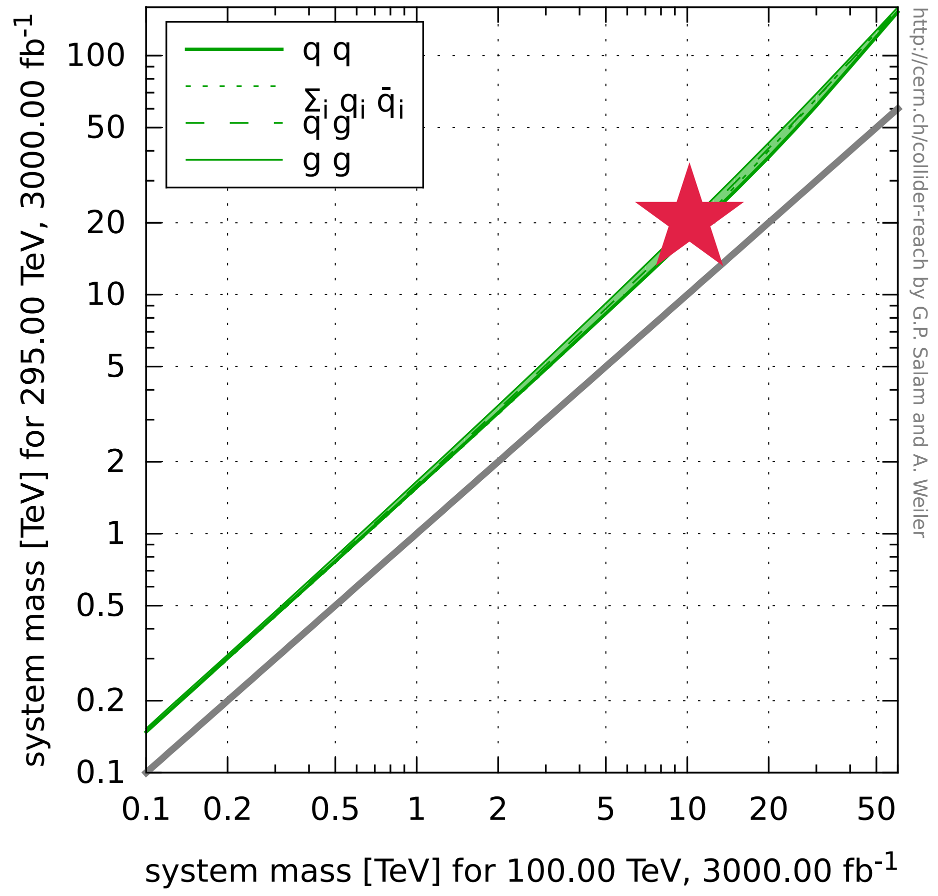
m_* → SM-charged states @ $m_* \lesssim \text{(loop)} \times \mathrm{m_h} \sim 20$ TeV; Requires pp machine @ $\sqrt{s} \sim 300$ TeV

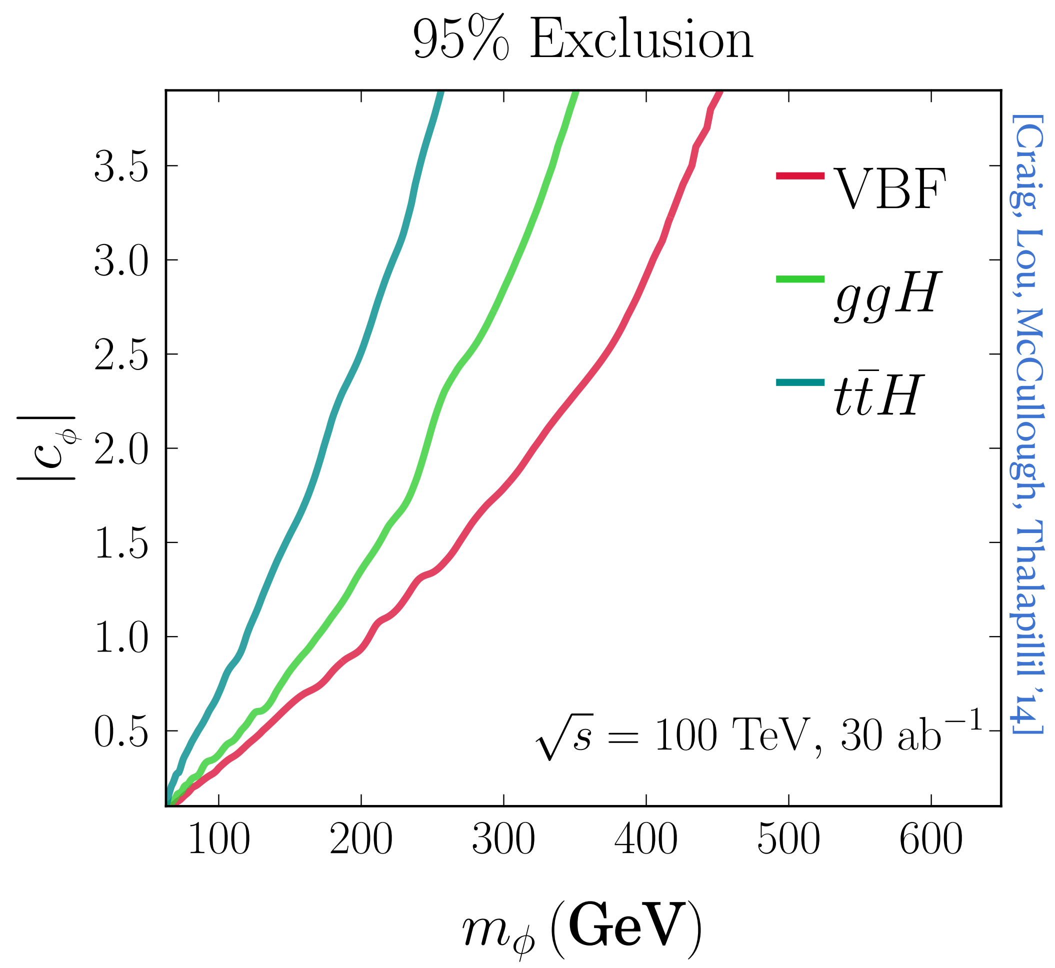
$\sqrt{1\ \text{loop}}$

$m_{h'}$ → SM-neutral states between 0.1-10 TeV; *Challenging target*; 100 TeV reach ~200 GeV

$\sqrt{1\ \text{loop}}$

m_h → Higgs coupling deviations at 1% level; Higgs decays to LLPs at 0.01% level





ElectroWeak Baryogenesis

Beautiful idea, but what if it just played out at higher scale based on new theory understanding?

100 TeV scale works fine

Unrestored Electroweak Symmetry

Patrick Meade (Stony Brook U.), Harikrishnan Ramani (UC, Berkeley) (Jul 19, 2018)

Published in: *Phys.Rev.Lett.* 122 (2019) 4, 041802 • e-Print: 1807.07578 [hep-ph]

High scale electroweak phase transition: baryogenesis \& symmetry non-restoration #30

Iason Baldes (DESY), Géraldine Servant (DESY and Hamburg U., Inst. Theor. Phys. II) (Jul 23, 2018)

Published in: *JHEP* 10 (2018) 053 • e-Print: 1807.08770 [hep-ph]

Electroweak Baryogenesis above the Electroweak Scale #27

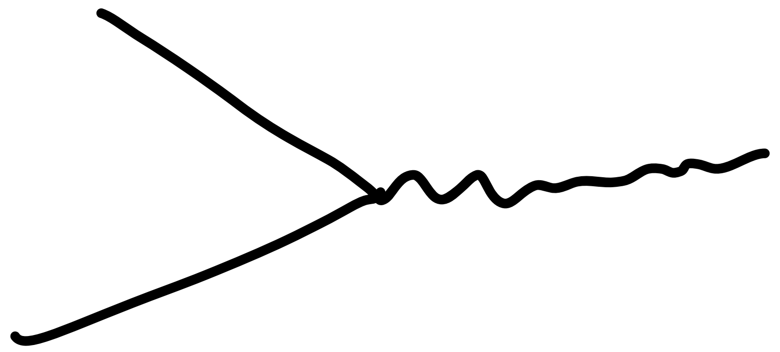
Alfredo Glioti (EPFL, Lausanne, LPTP), Riccardo Rattazzi (EPFL, Lausanne, LPTP), Luca Vecchi (EPFL, Lausanne, LPTP) (Nov 28, 2018)

Published in: *JHEP* 04 (2019) 027 • e-Print: 1811.11740 [hep-ph]

Energy gives precision

This mantra already exists for the LHC

Our standard QFT picture

 New physics!!

$$N_{events} = \sigma \cdot L \qquad \sigma \sim \frac{1}{E^2}$$

$$\sigma \downarrow \qquad L \uparrow$$

Standard unavoidable reason why we need Luminosity

Can we improve Higgs precision - Seems crazy?

Numerous reasons why you might want to (Flavor, ElectroWeak Phase Transition, Higgs Potential)

LEP 17 M Z's

"Major" BFs $\mathcal{O}(\%)$

Higgs Factory $\mathcal{O}(1)$ M H's

"Major" $\gamma\gamma \sim 10^{-3}$ $\sim 10^{3}$ events

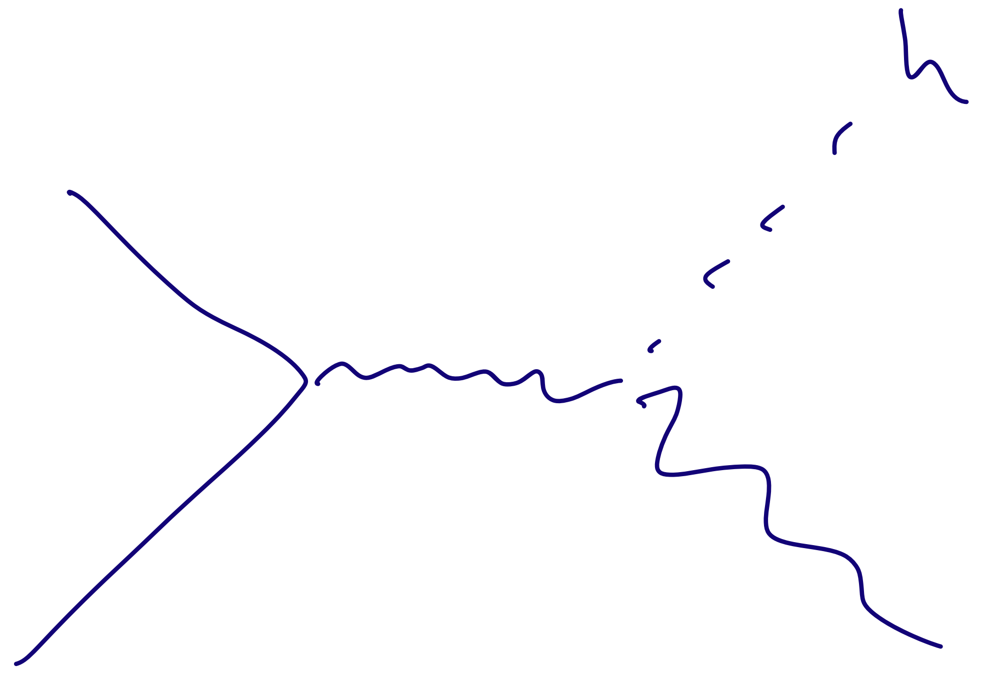
$\mu\mu \sim 10^{-4}$ $\sim 10^{2}$ events

$ss \sim 10^{-4}$

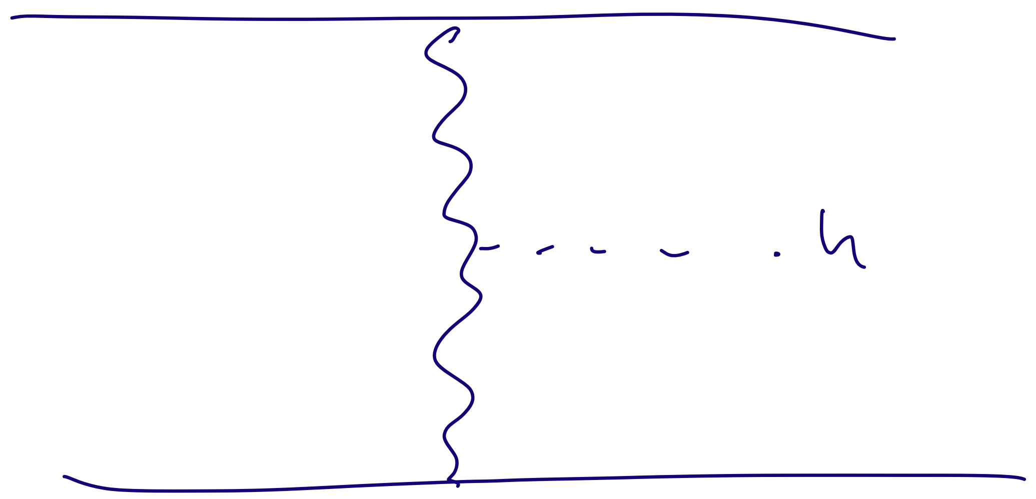
$u/d/e \sim 10^{-8}$ CRAP!!

FCC-ee (Tera Z program) - AC Giga+ Higgs?

Exploit kinematics to increase cross sections!



$$\sim \frac{1}{E^2}$$



$$\sim \ln E^2$$

$$N \sim \sigma L$$

$$\sigma \uparrow \qquad L \uparrow$$

Conclusions

- There is a simple case to make for Advanced Colliders - whether it can be a “shortcut” to 10 TeV or that we have a case to continue our march to the Planck scale,1, 10, 100 TeV…
- We need luminosity as well - simple consequence of QFT
- We need positrons or you are going to pay a strong reach penalty both for discovery and precision - can quantify based on interests
- Energy resolution - Bifurcation between “discovery” and doing precision with High Energy
- Even crazier ideas exist that you could pursue with compact colliders
- Now on to the real talks…